

# Distinguishing left- and right-handed molecules by two-step coherent pulses

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(Dated: August 24, 2010)

## Abstract

Chiral molecules with broken parity symmetries can be modeled as quantum systems with cyclic-transition structures. By using these novel properties, we design two-step laser pulses to distinguish left- and right-handed molecules from the enantiomers. After the applied pulse drivings, one kind chiral molecules are trapped in coherent population trapping state, while the other ones are pumped to the highest states for ionizations. Then, different chiral molecules can be separated.

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Chiral molecule lacks an internal plane of symmetry and consequently is not superposable on its mirror image. The coexistence of left- and right-handed chiral molecules (called “enantiomers”) originates from the fundamental broken symmetries in nature [1]. The physiological effect of enantiomers of biologically active compounds may differ significantly [2]. In general, only one enantiomeric form has the potential to be biologically beneficial, while the other one could be harmful or fatal. Thus, chiral purification and discrimination of enantiomers are fundamentally important tasks in pharmacology, biochemistry, etc [3]. Traditionally, various chromatographic separation methods, e.g., gas chromatography (GC), high performance liquid chromatography (HPLC), gas liquid chromatography (GLC) and thin layer chromatography (TLC) and so on [4], are widely utilized to achieve enantioseparation. Recently, certain optical means [5–8] were also proposed to implement the desirable purification. In particular, these chiral molecules are quantum systems with broken-parity symmetries and the usual electric-dipole selection rules do not hold. As a consequence, if only the three lowest levels are considered, a chiral molecule (left-handed or right-handed) can be treated as a quantum system with  $\Delta$ -type cyclic-transition structure. Note that cyclic transitions can also be realized in some other quantum systems, e.g., superconducting artificial atoms [9, 10]. Recent studies show that based on this novel property, by coupling these cyclic-transition molecules with optical fields can offer some new ways, e.g., cyclic population transfer [11, 12], generalized Stern-Gerlach effect [13], dynamical control [14], to achieve enantioseparation.

In this paper, we develop a dynamical method by using only two-step ultrashort coherent pulses to implement the desirable enantioseparation. Due to the fact that only dynamical ultrashort-pulse

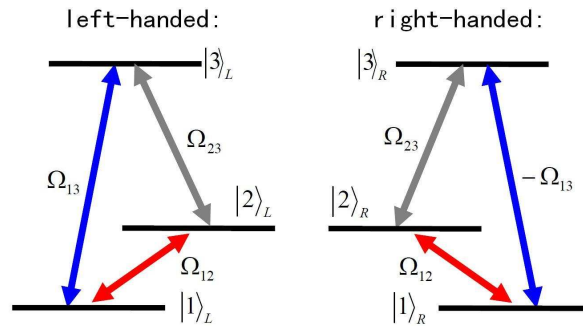


FIG. 1: (Color online) Three-level chiral molecules with cyclic transition structures. The enantiomers are resonantly driven by three optical fields with Rabi frequencies  $\Omega_{12}$ ,  $\Omega_{23}$ , and  $\pm\Omega_{13}$ , respectively.

operations are used, dynamical method will work faster and make decoherence effects less important [14]. In our protocol, both cyclic transition and coherent population trapping (CPT) [15–17] are utilized to achieve enantioseparation. A specific example of the chiral molecules with cyclic transition, e.g., is the  $D_2S_2$  enantiomers, as shown in Ref. [12]. Our basic idea is as follows: First, each enantiomer is prepared at the superposition of the two relatively lower states by applying an ultrashort  $\pi/2$  pulse. Subsequently, two pulses are simultaneously applied to couple these lower states to the highest one. Suppose that the Rabi frequencies of the pulses are chosen appropriately, so that for one kind chiral molecules, the state prepared in the first-step pulse operation can be just CPT state during the second-step pulses, while the other kind chiral molecules are pumped to the highest quantum state after a  $\pi$  rotation. Then, two kinds of chiral molecules can be separated by using ionization, followed by ions extraction by an electric field as suggested in Refs. [11, 14].

The transition structures of chiral molecules considered in this paper are schematized in Fig. 1. Here, only three lowest levels in the chiral molecules are considered, and thus each chiral molecule can be modeled as a three-level cyclic quantum system [11–14]. Three laser beams are applied to drive the enantiomeric molecules. The Hamiltonian of system can be written as

$$H = \sum_{i=1}^3 E_i |i\rangle \langle i| + \sum_{j>i=1}^3 [\Omega_{ij} e^{-i\omega_{ji}t} |j\rangle \langle i| + \text{h.c.}] \quad (1)$$

where  $E_i$  are the eigenvalues of energy eigenstates  $|i\rangle$ .  $\omega_{ij}$  are the frequencies, and  $\Omega_{ij}$  the Rabi frequencies of the applied coherent driving fields. Note that  $\Omega_{ij}$  should be regarded as complex parameters for the optical responses of quantum systems with loop transition structures are phase sensitive [11–14, 18]. Let  $\Delta_1 = E_3 - E_1 - \omega_{31}$ ,  $\Delta_2 = E_2 - E_1 - \omega_{21}$  and  $\Delta_3 = E_3 - E_2 - \omega_{32}$  be the detunings of the applied driving fields. When the resonant condition  $\Delta_i = 0$  is satisfied, in interaction picture, the interaction Hamiltonian can be written as:

$$H_I = \sum_{j>i=1}^3 [\Omega_{ij} |j\rangle \langle i| + \text{H.c.}] \quad (2)$$

One of a typical features in the present cyclic transition systems is that depending on the polarizations of the fields, one or all of the three Rabi frequencies  $\Omega_{ij}$  for the two kinds of chiral molecules differ by a sign [11, 12], i.e., the total phases of the three Rabi frequencies differ by  $\pi$  between the enantiomers. This means that the left- and right-handed molecules could be distinguished by a phase-dependent dynamical process applied to the enantiomers. Following the Refs. [12, 14], the Rabi frequencies for driving the left- and right-handed molecules are chosen as,  $\Omega_{ij}^L(t) = \Omega_{ij}(t)$ ,

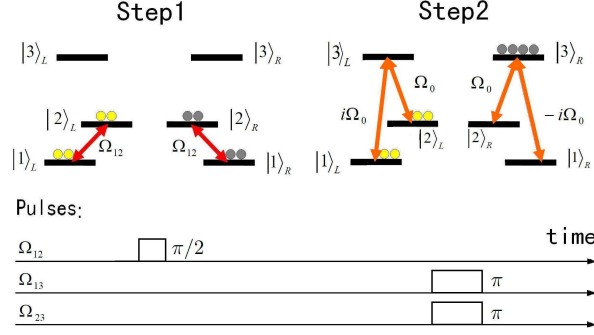


FIG. 2: (Color online) Schematic representation of the two-step pulse process to discriminate mixture of molecules. Step 1: Both left- and right- handed molecules are prepared in superpositions of their lower states  $|\psi_1\rangle_{L,R} = (|1\rangle_{L,R} - i|2\rangle_{L,R})/\sqrt{2}$  by a  $\pi/2$  pulse. Step 2: Two pluses are simultaneously applied to maintain the state  $|\psi_1\rangle_L$  invariant, but generate a  $\pi$ -rotation transferring the population in the state  $|\psi_1\rangle_R$  completely to the state  $-|3\rangle_R$  for ionizations

$\Omega_{13}^R(t) = -\Omega_{13}(t)$ ,  $\Omega_{12}^R(t) = \Omega_{12}(t)$ ,  $\Omega_{23}^R(t) = \Omega_{23}(t)$ . We assume the initial states of left- and right-handed molecules are their ground states  $|1\rangle_L$  and  $|1\rangle_R$ , respectively. To achieve the desirable enantioseparation, the left- and right-handed molecules should be engineered at the quantum states with different energies. To do this, we design the following two-step pulse process shown in Fig. 2.

Firstly, a  $\pi/2$  pulse with Rabi frequency  $\Omega_{12}(t) = \Omega_{12}^L(t) = \Omega_{12}^R(t)$  is applied to the mixture of chiral molecules for producing the superpositions of the lowest two energy-states. In this step,  $\Omega_{12}(t)$  is set as real parameter, i.e. its phase is zero. During this pulse the interaction Hamiltonians for the left- and right-handed molecules read

$$H_1^L = \Omega_{12} |2\rangle_{LL} \langle 1| + \text{H.c.}$$

and

$$H_1^R = \Omega_{12} |2\rangle_{RR} \langle 1| + \text{H.c.},$$

respectively. Clearly, the chiral molecules undergo the dynamical evolutions

$$|\Psi_1(t)\rangle_{L,R} = \cos\left(\int_0^t \Omega_{12} d\tau\right) |1\rangle_{L,R} - i \sin\left(\int_0^t \Omega_{12} d\tau\right) |2\rangle_{L,R}. \quad (3)$$

Obviously, if the duration of the applied pulse is designed as  $\int_0^t \Omega_{12} d\tau = \pi/4$ , namely a  $\pi/2$  pulse, the states of the enantiomers are prepared as  $|\psi_1\rangle_L = (|1\rangle_L - i|2\rangle_L)/\sqrt{2}$  and  $|\psi_1\rangle_R = (|1\rangle_R - i|2\rangle_R)/\sqrt{2}$  respectively.

Secondly, we apply simultaneously two pump pulses coupling transitions  $|1\rangle_{L,R} \leftrightarrow |3\rangle_{L,R}$  and  $|2\rangle_{L,R} \leftrightarrow |3\rangle_{L,R}$  with properly designed Rabi frequencies for evolving the different chiral molecules into different quantum states.

The Rabi frequencies of the second-step pulses could be designed as

$$\begin{aligned}\Omega_{13}^L(t) &= -\Omega_{13}^R(t) = \Omega_{13}(t) = i\Omega_0(t), \\ \Omega_{23}^L(t) &= \Omega_{23}^R(t) = \Omega_{23}(t) = \Omega_0(t),\end{aligned}\tag{4}$$

with  $\Omega_0(t) = |\Omega_{23}(t)| = |\Omega_{13}(t)|$ . The according Hamiltonians can be written as

$$H_2^L = \Omega' |3\rangle_{LL} \langle \Phi| + \text{H.c.}\tag{5}$$

$$H_2^R = \Omega' |3\rangle_{RR} \langle \Phi| + \text{H.c.}\tag{6}$$

with  $|\Phi\rangle_L = (-i|1\rangle_L + |2\rangle_L)/\sqrt{2}$ ,  $|\Phi\rangle_R = (i|1\rangle_R + |2\rangle_R)/\sqrt{2}$  and the effective Rabi frequency  $\Omega' = \sqrt{2}\Omega_0$ . It is easily checked that the state  $|\psi_1\rangle_L$  is a CPT state for the Hamiltonian (5) with zero eigen value (Note that  $|\psi_1\rangle_L$  is not belong to the subspace spanned by  $|\Phi\rangle_L$  and  $|3\rangle_L$ ). This means the state  $|\psi_1\rangle_L$  is unchanged after this operation, i.e.,  $|\psi_2\rangle_L = |\psi_1\rangle_L$ . While, for the right-handed molecules prepared in the state  $|\psi_1\rangle_R$  after the first step pulse, the dynamical evolution during this operation reads

$$|\Psi_2(t)\rangle_R = -i \cos\left(\int_0^t \Omega' dt\right) |\Phi\rangle_R - \sin\left(\int_0^t \Omega' dt\right) |3\rangle_R.\tag{7}$$

Obviously, after a  $\pi$  rotation for the effective Rabi frequency  $\Omega'$ , i.e.,  $\int_0^t \Omega' dt = \pi/2$ , the right-handed molecules evolve to  $|\psi_2\rangle_R = -|3\rangle_R$ . Note that during this process, the left-handed molecules always maintain the dark state  $(|1\rangle_L - i|2\rangle_L)/\sqrt{2}$ , as mentioned above.

Figs. 3 (a) and (b) give the the time evolution of populations  $P_i^{L,R}(t)$  in states  $|i\rangle_{L,R}$  for each kind chiral molecules under accurate two-step pulses. In our simulation, the applied Rabi frequencies are designed as following: in the first step, we start with a  $\pi/2$  pulse couples levels  $|1\rangle_{L,R}$  and  $|2\rangle_{L,R}$ , and has Rabi frequency  $\Omega_{12}(t) = \frac{\sqrt{\pi}}{4\tau} \text{Exp}[-(t-3\tau)^2/\tau^2]$ ; and in the second step, we simultaneously add two pulses with the Rabi frequencies  $\Omega_{13}(t) = \frac{i}{2\tau} \sqrt{\frac{\pi}{2}} \text{Exp}[-(t-9\tau)^2/\tau^2]$  and  $\Omega_{23}(t) = \frac{1}{2\tau} \sqrt{\frac{\pi}{2}} \text{Exp}[-(t-9\tau)^2/\tau^2]$  that couple  $|1\rangle_{L,R} \leftrightarrow |3\rangle_{L,R}$  and  $|2\rangle_{L,R} \leftrightarrow |3\rangle_{L,R}$ , respectively (Note that  $\Omega_{13}(t)$  and  $\Omega_{23}(t)$  can generate an effective  $\pi$  rotation between states  $|\Phi\rangle_{L,R}$  and  $|3\rangle_{L,R}$  with Rabi frequency  $\Omega'(t) = \frac{\sqrt{\pi}}{2\tau} \text{Exp}[-(t-9\tau)^2/\tau^2]$ ). If the left- and right-handed molecules are initially prepared in their ground states  $|1\rangle_L$  and  $|1\rangle_R$ , after this accurate two-step

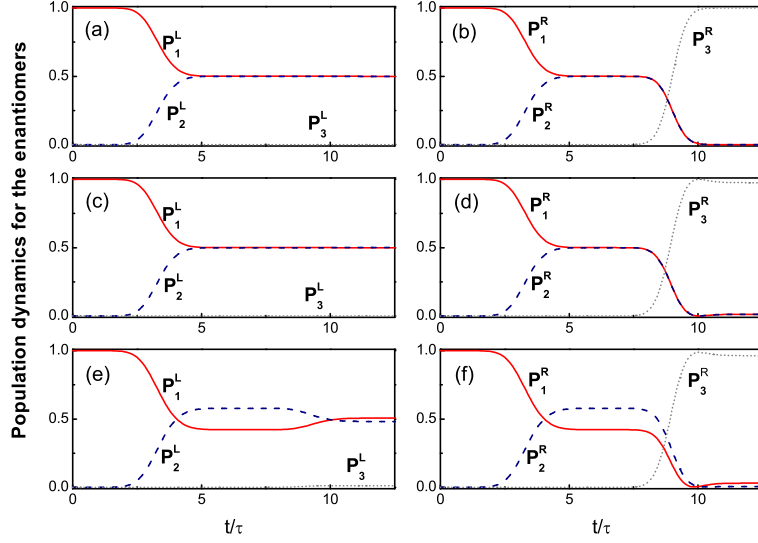


FIG. 3: (Color online) The time evolution of the population of the chiral molecules. Both enantiomers start in their ground states  $|1\rangle_{L,R}$ . Subplots (a) and (b): The two step-pulses are accurate. At the end of the process, the left-handed molecules are completely trapped in  $|1\rangle_L$  and  $|2\rangle_L$  states, while the right-handed molecules are totally pumped to  $|3\rangle_R$  state. Subplots (c) and (d): The pulse duration in the second step are inaccurate. After pulse operation, the left-handed molecules are not influenced and completely trapped in  $|1\rangle_L$  and  $|2\rangle_L$  states, while the right-handed molecules are partially pumped to  $|3\rangle_R$  state. Subplots (e) and (f): All the pulses, including their durations and the relative phase of the two pulses used in the second step, are inaccurate (Here we assume all these quantities are with 10% deviation from idea values.). After pulse operation, the left-handed molecules are still mostly populated in  $|1\rangle_L$  and  $|2\rangle_L$  states, and the right-handed molecules are nearly pumped to  $|3\rangle_R$  state. This shows that the two-step pulse approach is robust, even the operations are imperfect.

pulse process, the final populations of left- and right-handed molecules are  $p_1^L = p_2^L = 1/2$ ,  $p_3^L = 0$  and  $p_1^R = p_2^R = 0$ ,  $p_3^R = 1$ , as shown in Figs. 3 (a) and (b).

Given the two kinds of chiral molecules evolving to different states with different energies after the above two-step pulses, an ionization process, as suggested in Ref. [11], can be utilized to separate them. Specifically, in our case, by appropriate ionization energies, the right-handed molecules prepared in the highest levels can be ionized but the left-handed ones populating in the superposition of two lower states remain unchanged. Followed by the ions extractions via an

electric field, the mixture of enantiomers can be finally separated.

Practically, in the two-step pulse process, the Rabi frequencies, either the intensities or the phases, may be inaccurate. Now we begin to discuss the influence of all these deviations on the enantioseparation. At first, we assume that in the first step, the applied pulse deviate from perfect  $\pi/2$  pulse and according Rabi frequencies then could be written as  $\Omega_{12}^L = \Omega_{12}^R = \Omega_{12} = \tilde{\Omega}_{12} + \delta\tilde{\Omega}_{12}$ , with  $\int_0^t \tilde{\Omega}_{12} dt = \frac{\pi}{4}$ ,  $\int_0^t \delta\tilde{\Omega}_{12} dt = \Delta$ . Clearly, after this pulse operation, the states of the enantiomers are prepared as

$$|\psi_1'\rangle_{L,R} = \cos \Delta \frac{1}{\sqrt{2}} (|1\rangle_{L,R} - i|2\rangle_{L,R}) - \sin \Delta \frac{1}{\sqrt{2}} (|1\rangle_{L,R} + i|2\rangle_{L,R}). \quad (8)$$

In addition, we assume that in the second step, the simultaneously applied two pump pulses are also imperfect ones with Rabi frequencies  $\Omega_{13}^L(t) = -\Omega_{13}^R(t) = \Omega_{13}(t) = e^{i(\frac{\pi}{2} + \delta\phi)} (\tilde{\Omega}_0 + \delta\tilde{\Omega}_0)$ ,  $\Omega_{23}^L(t) = \Omega_{23}^R(t) = \Omega_{23}(t) = \tilde{\Omega}_0 + \delta\tilde{\Omega}_0$ , where  $\delta\tilde{\Omega}_0$  and  $\delta\phi$  represent the deviations of amplitude and phase of Rabi frequency. Let  $\Omega' = \tilde{\Omega}' + \delta\tilde{\Omega}' = \sqrt{2} (\tilde{\Omega}_0 + \delta\tilde{\Omega}_0)$ , the effective Hamiltonian describing this step can be written as

$$H_2'^L = \Omega' |3\rangle_{LL} \langle\Phi'| + \text{H.c.} \quad (9)$$

$$H_2'^R = \Omega' |3\rangle_{RR} \langle\Phi'| + \text{H.c.} \quad (10)$$

with  $|\Phi'\rangle_L = \frac{1}{\sqrt{2}} (-ie^{-i\delta\phi} |1\rangle_L + |2\rangle_L)$ ,  $|\Phi'\rangle_R = \frac{1}{\sqrt{2}} (ie^{-i\delta\phi} |1\rangle_R + |2\rangle_R)$ . We can define the states  $|\varphi'\rangle_L = \frac{1}{\sqrt{2}} (|1\rangle_L - ie^{i\delta\phi} |2\rangle_L)$  and  $|\varphi'\rangle_R = \frac{1}{\sqrt{2}} (|1\rangle_R + ie^{i\delta\phi} |2\rangle_R)$ , which are orthogonal to  $|\Phi'\rangle_L$  and  $|\Phi'\rangle_R$ , respectively. Thus, the initial states of left- and right-handed molecules of the second pulse operation can be rewritten as

$$|\psi_1'\rangle_{L,R} = A_{L,R} |\Phi'\rangle_{L,R} + B_{L,R} |\varphi'\rangle_{L,R} \quad (11)$$

with  $A_{L,R} = \frac{1}{2} i [\pm \cos \Delta (e^{i\delta\phi} \mp 1) \mp \sin \Delta (e^{i\delta\phi} \pm 1)]$ ,  $B_{L,R} = \frac{1}{2} [\cos \Delta (1 \pm e^{-i\delta\phi}) - \sin \Delta (1 \mp e^{-i\delta\phi})]$ . Obviously, in the second pulses process, the dynamical evolution of the chiral molecules reads

$$|\Psi_2'(t)\rangle_{L,R} = A_{L,R} \cos \left( \int_0^t \Omega' dt \right) |\Phi'\rangle_{L,R} - iA_{L,R} \sin \left( \int_0^t \Omega' dt \right) |3\rangle_{L,R} + B_{L,R} |\varphi'\rangle_{L,R}. \quad (12)$$

Clearly, after an imperfect  $\pi$  rotation with the effective Rabi frequency  $\Omega' = \tilde{\Omega}' + \delta\tilde{\Omega}'$  (Here we assume that  $\int_0^t \tilde{\Omega}' dt = \frac{\pi}{2}$ ,  $\int_0^t \delta\tilde{\Omega}' dt = \Delta'$ ), the left- and right-handed molecules evolve to the states

$$|\psi_2'\rangle_{L,R} = -A_{L,R} \sin \Delta' |\Phi'\rangle_{L,R} - iA_{L,R} \cos \Delta' |3\rangle_{L,R} + B_{L,R} |\varphi'\rangle_{L,R}. \quad (13)$$

As a consequence, the final populations of the enantiomers for the small  $\Delta$ ,  $\Delta'$ ,  $\delta\phi$  read

$$p_{1,2}^L \approx \frac{1}{2} \left[ 1 - \Delta^2 \pm 2\Delta\Delta' - \frac{1}{4}(\delta\phi)^2 \right], \quad (14)$$

$$p_3^L \approx \frac{1}{4}(\delta\phi)^2 + \Delta^2, \quad (15)$$

$$p_{1,2}^R \approx \frac{1}{2} \left[ (\Delta' \pm \Delta)^2 + \frac{1}{4}(\delta\phi)^2 \right], \quad (16)$$

$$p_3^R \approx 1 - \Delta^2 - \Delta'^2 - \frac{1}{4}(\delta\phi)^2. \quad (17)$$

Now we give some discussion on the above results. If the states prepared in the first step are perfect, then, in the second step, even if inaccurate pulse amplitude (or duration) lead to deviation of perfect  $\pi$  pulses (Here, we assume that Eq. (4), i.e., CPT condition  $\Omega_{13}(t)/\Omega_{23}(t) = i$  for left-handed molecules, should still be satisfied.), purification of the right-handed molecules can also be effectively performed. To show this, we let  $\Delta = 0$ ,  $\delta\phi = 0$  in Eq. (14)-(17) and thus the final populations in this case are  $p_{1,2}^L \approx \frac{1}{2}$ ,  $p_3^L \approx 0$ ,  $p_{1,2}^R \approx \frac{1}{2}\Delta'^2$ ,  $p_3^R \approx 1 - \Delta'^2$ , respectively. This means that the left-handed molecules can be trapped in a superposition state of the two lower states, i.e., the CPT state  $|\psi_1\rangle_L$ , while right-handed molecules can still be *partially* pumped to the higher state under imperfect  $\pi$  pulses, and then purified by the following ionization process. Note that in this case not both enantiomers can be perfectly purified, as not only left-handed molecules but also partial right-handed ones populate in the two lower states ( $p_{1,2}^R \approx \frac{1}{2}\Delta'^2$ ). Thus, after ions formed by right-handed molecules extracted by an electric field, the remainder is still mixture of two enantiomers. But this is still meaningful, since in most cases only one enantiomer may produce the desired therapeutic (or biological) activities and thus we should extract merely the biologically beneficial chiral molecules from mixtures of enantiomers. To confirm the above analysis, Figs. 3 (c) and (d) present a numerical simulation of the population dynamics for the left-handed and right-handed molecules initially prepared in states  $|1\rangle_L$  and  $|1\rangle_R$  and driven by pulses with Rabi frequencies  $\Omega_{12}(t) = \frac{\sqrt{\pi}}{4\tau} \text{Exp}[-(t-3\tau)^2/\tau^2]$ ,  $\Omega_{13}(t) = \frac{i}{2\tau} \sqrt{\frac{\pi}{2}} \text{Exp}[-(t-9\tau)^2/(1.1\tau)^2]$ , and  $\Omega_{23}(t) = \frac{1}{2\tau} \sqrt{\frac{\pi}{2}} \text{Exp}[-(t-9\tau)^2/(1.1\tau)^2]$ , respectively (Note that  $\Omega_{13}(t)$  and  $\Omega_{23}(t)$  can generate an effective  $\pi$  rotation between states  $|\Phi\rangle_{L,R}$  and  $|3\rangle_{L,R}$  with Rabi frequency  $\Omega'(t) = \frac{\sqrt{\pi}}{2\tau} \text{Exp}[-(t-9\tau)^2/(1.1\tau)^2]$ , leading to a deviation of  $\pi$  pulse:  $\Delta' \approx 0.1 \times \frac{\pi}{2}$ ). It can be seen from Figs. 3 (c) and (d) that the left-handed molecules are finally populated in the two lower states  $|1\rangle_L$  and  $|2\rangle_L$  with  $p_1^L = p_2^L = 1/2$ , the right-handed molecules are mostly populated in state  $|3\rangle_R$  with  $p_3^R \approx 0.976$  and slightly populated in state  $|1\rangle_R$  and  $|2\rangle_R$  with  $p_1^R \approx p_2^R \approx 0.012$ .



For the more general case that all the applied Rabi frequencies in the two steps, either the intensity or the phase, are inaccurate, Eq. (14)-(17) give the final population of enantiomers theoretically. For a numerical simulation of population dynamics, we assume that the Rabi frequencies are designed as  $\Omega_{12}(t) = \frac{\sqrt{\pi}}{4\tau} \text{Exp}[-(t-3\tau)^2 / (1.1\tau)^2]$ ,  $\Omega_{13}(t) = \frac{\sqrt{2\pi}}{4\tau} \text{Exp}[-(t-9\tau)^2 / (1.1\tau)^2 + i\frac{11\pi}{20}]$  and  $\Omega_{23}(t) = \frac{\sqrt{2\pi}}{4\tau} \text{Exp}[-(t-9\tau)^2 / (1.1\tau)^2]$ , respectively. Again, note that  $\Omega_{12}(t)$  can lead to a deviation of  $\pi/2$  pulse  $\Delta \approx 0.1 \times \frac{\pi}{4}$ ;  $\Omega_{13}(t)$  and  $\Omega_{23}(t)$  can generate an effective rotation between states  $|\Phi'\rangle_{L,R}$  and  $|3\rangle_{L,R}$  with Rabi frequency  $\Omega'(t) = \frac{\sqrt{\pi}}{2\tau} \text{Exp}[-(t-9\tau)^2 / (1.1\tau)^2]$ , leading to a phase imperfection  $\delta\phi \approx 0.1 \times \frac{\pi}{2}$  and a deviation of effective  $\pi$  pulse  $\Delta' \approx 0.1 \times \frac{\pi}{2}$ . Under these pulses, the time evolution of population of enantiomers are shown in Figs. 3 (e) and (f). Our numerical calculation shows that after the pulses given above, the final populations  $p_1^L + p_2^L \approx 0.988$ ,  $p_3^R \approx 0.964$ , which is in accordance with theoretical evaluations given by Eq. (14)-(17). Obviously, these results show that if the applied pulses do not deviate very large from perfect ones, after pulse operation, the left-handed molecules can be almost populated in states  $|1\rangle_L$  and  $|2\rangle_L$ , and the right-handed ones can be nearly populated in state  $|3\rangle_R$ . Moreover, note that in practice the applied pulses can be more accurate than those used in our simulation and the influence of this inaccuracy is more less. Thus, even the given pulses are not so much perfect, the enantiomers can also be effectively prepared in different final states.

Certainly, during the second driving process, the Rabi frequencies can also be designed as

$$\begin{aligned}\Omega_{13}^L(t) &= -\Omega_{13}^R(t) = \Omega_{13}(t) = -i\Omega_0(t), \\ \Omega_{23}^L(t) &= \Omega_{23}^R(t) = \Omega_{23}(t) = \Omega_0(t).\end{aligned}\tag{18}$$

In this case, the right-handed molecules are trapped in the dark state  $|\psi_1\rangle_R$  and thus unchanged after the pulses, while the left-handed ones are pumped to the higher state. Thus, after pulse operation, similar ionization and ions extraction processes can be implemented to separate the enantiomers.

In conclusion, we have introduced a two-step optical pulses method to enantioseparations. In our protocol, the pulse processes are simplified by trapping one kind of chiral molecules in CPT states and the others are evolved to the highest levels for ionization. Compared with the previous three-step pulse method [14], our two-step operational approach is more robust in the presence of decoherence for less pulse steps means shorter operation time. Additionally, even if the applied pulses are inaccurate, the enantiomers can also be effectively prepared in different final states and be separated. Finally, in our method lower ionization energy is required, as the left(right)-handed

molecules are prepared in their highest states.

### Acknowledgments

The project was supported in part by National Natural Science Foundation of China under Grant Nos. 10874142, 90921010 and the National Fundamental Research Program of China through Grant No. 2010CB923104.

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